PHOTOGRAMMETRY BASED ERROR ANALYSIS OF INDOOR MOBILE ROBOT LOCALIZATION *

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ABSTRACT

The presented work is a low cost "off-line" method that is able to evaluate the precision of mobile robot localization, which is a difficult task. A reference path is yielded by a drawing pen attached to indoor mobile robot, which also adds timestamps to the trace on the floor. The method is based on comparing the reference path obtained using photogrammetry, with the results of several localization algorithms on board of mobile robots. At the moment, different techniques exist that deal with that problem, but these are either expensive or too rigid.

1. INTRODUCTION

Nowadays, there are a lot of methods and algorithms that can be used in order to compute mobile robot localization. Knowing the robot position in working space is the base to do path tracking or to generate a map of the environment (SLAM). Thus, precision in this data must be granted. Depending on the destination application of the mobile object, localization will require higher or lower degrees of precision. This precision will be determined by the quality of both the sensors and the localization algorithm.

As it is introduced in the *abstract* it is difficult to measure the precision with which a mobile robot position is computed. Many factors are concerned in this difficultness, like the own movement of the robot. The speed of these robots is usually not quite high, but enough to make static and precise measuring methods impossible to use (topographic triangulation, laser metrology, etc.)

It must be noted that the robot localization algorithm must be run in real-time in order to better controlling the robot, i.e. it must be "on-line". However, in order to test localization method precision this restriction may not necessarily be followed, so we can talk about "off-line" methods for measuring the precision in mobile robot localization. Afterwards they can be compared with "on-line" obtained data. In order to make this comparison it is essential to have timestamps for measure synchronization, as will be explain in section 2.

At the moment, there are several methodologies that help in solving the problem that this paper deals with. We have found two different methods, being both very expensive but providing very high performance. First of them are the innovative tracking lasers used for metrology, like the LT800 model from Leica GeoSystems [1]. It allows tracking a reflector at a maximum speed of 6 m/s with very high precision and capturing 3000 points every second. We only need to attach a reflector to the mobile robot of which we want to know the position. This measuring technique is also "on-line" and external to the mobile robot.

Another high cost method is using precise inertial systems, like the ones developed in PINS project [2], using atomic accelerometers, or the ones manufactured by iMAR [3], intended for specific guidance applications with high precision and very low drift. The problems of this method, in addition to its high economic cost, are the typical problems of inertial systems and dead-reckoning [4], [5]. Normally these systems are used for the own localization algorithm, since they offer "on-line" data and are propioceptive, but not to test the precision of the localization method, due to their high cost, as mentioned before.

Another method is the use of rails for the guidance of the robot. This system is little flexible since the accomplishment of a new trajectory implies the change of the infrastructure. The precision in the topographic measurement of the position of the rails, over which the movable object will circulate, can be very high, becoming

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the reference path. Moreover, timestamps can be obtained by means of optical barriers. An example of this is the circuit built in *Laboratoire Central des Ponts et Chaussées* (LCPC) in France, also called SESSYL [6]. The comparison between the localization algorithm and the reference path must be done in post process, thus this is an "off-line" method.

Another low cost "on-line" method is using a calibrated camera, mounted on the robot at constant height with respect to the floor and normal to it. Images obtained by the camera allow the detection of certain codified marks painted in the floor or textures, knowing their position precisely. An alternative to this is doing correlation between the obtained image and a photographic mosaic of the floor [10]. The problems of these methodologies are illumination and the little camera view angle.

Other authors [12] use theodolites for measuring the robot localization.

The method presented in this paper, i.e. photogrammetry method, allows obtaining a good precision, next to one millimetre, in determining a reference path, with a relatively low cost. The reference path is a trace drawn by a known point of the robot while doing a trajectory. The tracer allows marking different patterns in the surface by where the mobile robot moves, that will serve later as timestamps. In fig. 1 we can see the TAP mobile robot equipped with the tracer

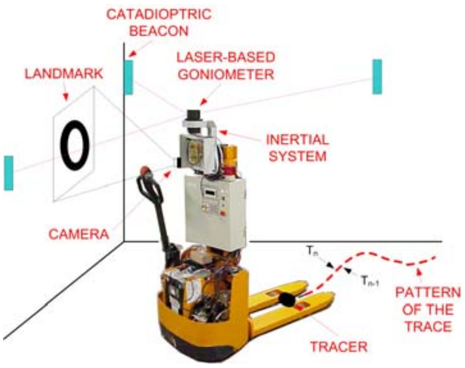

Fig. 1: The mobile robot TAP and the trace of the reference path

Different sensors might be mounted in this robot [11] in order to implement several localization algorithms, so that we are able to test, by comparing with reference path, later their precision using the presented method.

2. METHOD BASIC IDEAS

In order to test the precision of mobile robot localization algorithms, the proposed methodology assumes a set of requirements, shown in the following list:

I. The mobile robot is in movement.
II. At an instant of time perfectly determined (t) we have to know the real position of the mobile robot (reference points).
III. At the same moment (t), the localization algorithm tested, has to compute the mobile robot position.

The main difficulty of the previously mentioned requirements, is obtaining the necessary data at the same instant (t).

The photogrammetric method consists of a tracer placed in some known point of the mobile robot, which leaves a visible trace with timestamps on the floor that must later be photographed. On the floor identifiable points must exist whose position is known with high precision, which is the CAD model, so a geometric registration among the captured image and the CAD model can be done. From this moment the trace left by the mobile robot is available, accurately located in the model. The only thing left to do is to extract both the reference path and timing information from the trace marks. Finally, we compare the localization algorithm with the reference path at the same instant of time.

Below there is a description of the necessary components and processes needed at each stage.

2.1. Tracer

The tracer device is formed by an electro mechanic head (plotter head), where the nib has been replaced by a hard-end pen. The head contains an electromagnet that provides the nib with vertical movement, when it is electrically excited. As it can be seen in fig. 2, our head has a travelling distance of 7.6 mm and the exciting signal comes from the robot control unit, allowing to make different trace patterns, at the desired instant (t).

The nib's ink can easily be erased from the floor with alcohol, but not while the robot moves over. To distinguish among different trajectories, or to make the drawing visible from the floor texture, we may use nibs of many colours. The hardness of the nib's end prevents the thickness of the trace (1 mm) from excessive variations in a 20 m trajectory. However, it should be changed in order to carry out a new trajectory.

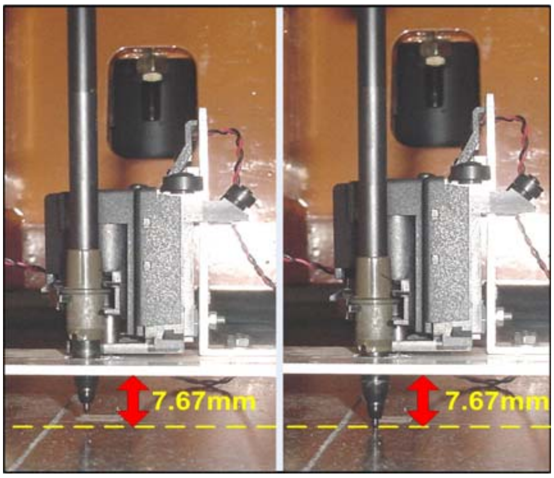

Fig. 2: Tracer head up / down

The time to contact of the nib has been computed by means of an optical barrier, with a mean of 30 ms and a standard deviation about 1.497 ms. Thus, the patter will be able to be changed at a maximum frequency of 33 Hz.

To obtain the orientation of the mobile robot two tracers are necessary and they must go down in the same instant of time.

2.2. Marks on the floor and image resolution

The proposed method needs placing marks on the floor, and having them accurately measured, fig. 3 (CAD model). This can be achieved using topographical tools. Table 1 shows a comparison of the measuring precision, taken with several models of Leica Geosystems tachymeters. This allows us to obtain a mark measuring precision of up to 0.5 mm, depending on the used device.

Model	X+	X-	Y+	Y-
TCR403	2.996	-2.996	2.484	-2.430
TCR702	1.997	-1.997	1.656	-1.620
TCA2003	0.499	-0.499	0.414	-0.405

Table 1: Different Leica models maximum and not absolute error in a point location (X,Y) (in mm).

The number of viewed marks, placing on the floor, depends on the field of view of the camera.

The photogrammetric method requires of some image properties to guarantee its function. In our case the camera were placed in a tripod, hold at a fixed known height from the floor where it is able to photograph a 1 x 0.7 m. rectangle, and its CCD has 2580 x 1720 pixels, each pixel will hold an area of 0.3 x 0.4 mm. It is mandatory that two marks appear in each photograph in order to correctly orientate the photographs over the surface map. Thus, we must ensure that two marks always exist in the area of an

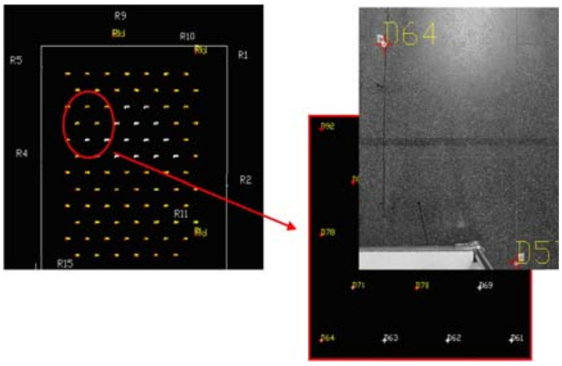

Fig. 3: CAD model of the floor

image (1 x 0.7 m). If the ground has floor tiles, a good method is measuring tile corners, every two or three of them, depending on their size, fig. 3.

2.3. Types of traces

Selecting the type of pattern in the trace is a fundamental decision, since this pattern will define the timestamps. The kind of pattern must assure that the traces will be neither overlapped nor excessively separated, so it is important that the excitation signal varies accordingly with the mobile robot speed.

If the requirement I in section 2 needs to be infringed, i.e. the robot is stopped in any point of the trajectory, the tracer excitation must also be stopped, in order to avoid overlapping of tracer marks, and writing it down in localization data stored in the control unit.

3. PHOTOGRAMMETRIC METHOD

The photogrammetric method consists on obtaining orthophotos of the reference path with a calibrated camera. Afterwards captured images must be matched with the CAD model of floor marks an so it will allows us to measure in the matched map.

3.1 Photographic camera calibration

Camera calibration is a vital step, since all the robot's trace must be photographed. For taking images a tripod is used, where the camera is installed at a fixed height and normal respect to the floor.

Camera calibration parameters		
Focal Length	2985.19 ± 8	2979.84 ± 7.9
Principal Point	1309.8 ± 8.6	823.45 ± 6.6
Pixel error	0.928	0.735
Distortion parameters	[-0.15807 0.29258 -0.00229 0.00073 0.00000] ± [0.00936 0.05512 0.00056 0.00070 0.00000]	

Table 2: Results of camera calibration (units in pixels)

The camera calibration calculates the different distortions that appear in captured images. It has been computed by means of Matlab *Calibration Toolbox* made by ©Jean-Yves Bouquet, based on [7] and [8], among others. Table 2 shows the obtained results.

3.2. Geometric registration

Once undistorted images of all the trace have been obtained, assuring that at least two measured floor marks appear, images are superposed over the CAD model.

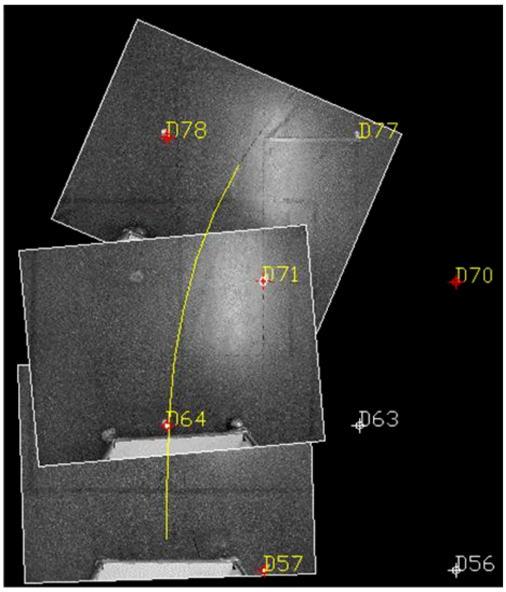

Fig. 4: Polyline marks the referente path

Afterwards, a polyline must be manually (automatic in future) traced over the photographed trajectory, fig. 4, working with an appropriate zoom level, paying special attention to the end points of the line because there are the timestamps.

3.3. Comparing reference path with robot localization

The test consists in comparing the reference path (polyline points) with the points of the localization algorithm stored at the robot control unit, where the time is used for synchronizing both paths.

It must be noticed that in this comparison we have to take into account the tracer delay.

The data obtained with the method, either the points of the reference path or those coming from the localization algorithm allow using different error measurements.

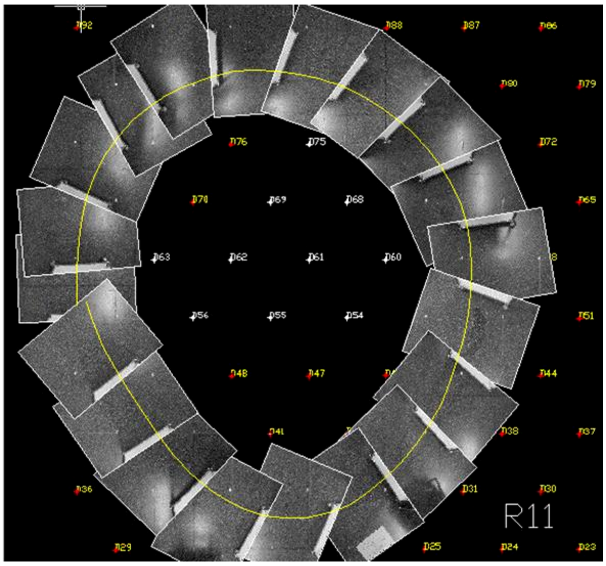

Fig. 5: Whole trace over the CAD model

The mobile robot orientation would be the vector between two points of the tracers at same time (t). In this work we start focusing in the x, y position.

4. EXPERIMENT SETUP

Photogrammetric method has been used in our labs with the TAP mobile robot. This robot has tricycle kinematics, with one steering and driving wheel, placed away from the centre (C). Fig. 6 shows its schematics, where it must be noted the P point, being the reference point of a laser goniometer. Point C is the centre of the steering and driving wheel and it is the base on odommetric sensors. The same figure also shows the basic dimensions of TAP (L, Lp and O), as well as the mounted tracer, located in the forks central point.

The measures obtained in the assembly of the tracer in TAP robot (fig. 6 zoom), it is possible to have a transformation matrix between the nib's end and either P or C, depending on which of both better fulfills our needs. This transformation must be made previously to what is explained in 3.2; otherwise the localization data could not be compared.

The TAP mobile robot is provided with a control unit which allows to capture any data needed by the

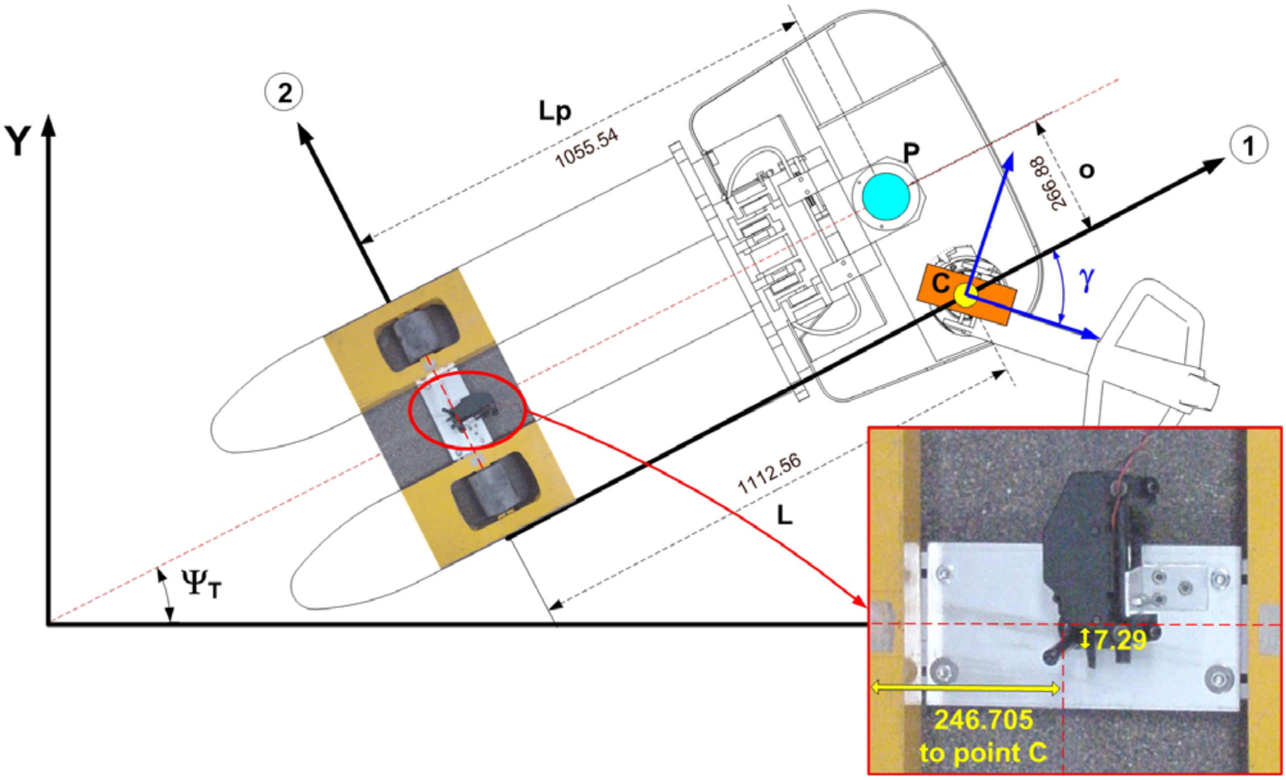

Fig. 6: The robot with the tracer (units in mm)

localization algorithm, as well as to control the tracer. In our case, the localization algorithm is dynamic localization based on laser-based goniometer [9].

In the performed experiment, the TAP mobile robot has been manually driven, in order to obtain the trajectory shown in fig. 5.

4.1. Analysis of the precision obtained by the method in the experiment setup

The errors of precision in the presented method are caused by four factors: camera calibration errors, marks measuring errors, time to contact of tracer and precision of TAP parameters.

The precision in the measuring of marks depends on the precision of the method used for it. If we use a theodolite, we must know its precisions, see table 1. In our case we used model TCR2003 of Leica Geosystems, with an approximate precision of half millimetre.

The TAP parameters measuring, which can be observed in fig. 6, have been obtained with metrology laser tools and their precision is inferior to one millimetre.

One of the parameters which add most uncertainty to the method is the tracer delay. As mentioned before, the delay between tracer excitation and the moment when nib reaches floor surface has been obtained by means of multiple repetitions. The mean of the times obtained is 30 ms, with a standard deviation of 1.5 ms.

Matlab toolbox for camera calibration offers information about calibration error measured in pixels. In our case, table 2 shows that the mean of the error in pixel reprojection is 0.928 x 0.735. By knowing the size of each pixel, see 3.2, we can calculate that the mean of the error in undistorted image is 0.278 x 0.294 mm. Standard deviation in pixel reprojection is ±1.95 pixels, so standard deviation in undistorted image error is 0.585 x 0.78 mm.

Therefore, the maximum precision that the presented method may reach directly depends on the mobile robot moving speed, as well as the error generated by the tracer delay. This precision must be added with the undistorted image error (1 mm), and the tolerance in floor marks and robot parameters measuring. In our case, the precision is close to ± *(1 + std[tracer_delay]·TAP_speed)* mm. Thus, with a speed of 0.4 m/s and a standard deviation of 1.5 ms, the obtained precision is ±1.6 mm.

5. EXPERIMENT RESULTS

The comparison of dynamic localization with laser-based goniometer [9] with a photogrammetry reference path is used to illustrate the error analysis; some results can be appreciated in fig. 7.

Table 3 shows the result obtained for lateral error (ε) equation (1) between reference path and the sample of the localization algorithm. This is one of the possible ways of kindness measuring, as well as position error, MSE, …

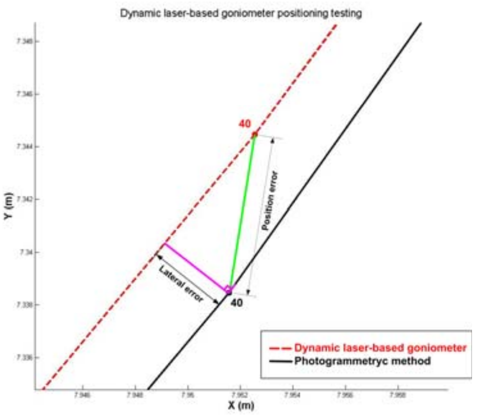

Fig. 7: Comparing localization algorithm

$$\begin{cases} \begin{cases} \varepsilon = (Y_P - Y_{Ai}) \cdot \cos\psi_{ti} - (X_P - X_{Ai}) \cdot \sin\psi_{ti} \\ \psi_{ti} = \operatorname{atan2}\left(\dfrac{Y_{Bi} - Y_{Ai}}{X_{Bi} - X_{Ai}}\right) \end{cases} \rightarrow \text{line} \\ \varepsilon = \sqrt{(X_D - X_P)^2 + (Y_D - Y_P)^2} - R_i \rightarrow \text{arc} \end{cases} \quad (1)$$

Where (X_{Ai}, Y_{Ai}) and (X_{Bi}, Y_{Bi}) are the initial and end coordinates of rectilinear segment of reference path, ψ_{ti} is the orientation angle of the path, R_i the radius of arc segment and (X_D, Y_D) the centre of the arc.

Variable	Mean	Standard deviation
$\lvert e_{lat} \rvert$ (dynamic)	5 mm	4,2 mm

Table 3: Comparison results

6. CONCLUSIONS

In this work a method has been presented to compare the precision of different mobile robot localization algorithms. Main advantages are its low cost and high precision, close to 2 mm. The presented off-line method needs a post processing phase. The frequency of testing is low (33 Hz), since the tracer is a mechanical element that requires a certain time to make its movement.

In a future work it is planned to use two tracers to obtain robot orientation and also the portions of the pattern painted by the nib in the floor to improve the method.

7. REFERENCES

[1] Leica Geosystems, "LT(D)800 Datasheet" http://www.leicageosystems.com/metrology/en/products/laser_tracker/lgs_1375.htm.

[2] PINS Project, DARPA, http://www.darpa.mil/dso/thrust/matdev/pins.htm.

[3] IMAR web page, http://www.imar-navigation.de/englishside/imar.htm

[4] B. Barshan, H. F. Durrant-Whyte, "Inertial Navigation Systems for Mobile Robots", IEEE Transactions on Robotics and Automation, vol. 11, no. 3, June 1995

[5] J. Borenstein, H.R. Everett, L. Feng, *Where am I? Sensors and methods for mobile robot localization*, University of Michigan, 1996.

[6] LCPC "Test facility on localization systems SESSYL", http://www.lcpc.fr/en/presentation/moyens/sessyl/index.dml

[7] Z. Zhang, "Flexible Camera Calibration by Viewing a Plane from Unknown Orientations", ICCV, 1999.

[8] J. Heikkilä, O. Silvén, "A Four-step Camera Calibration Procedure with Implicit Image Correction", CVPR, 1997

[9] J. Agulló , J. M. Font, J. Escoda, "Dynamic localization of a mobile robot using a laser-based goniometer". IEEE IFAC Symposium on Intelligent Autonomous Vehicles. Lisboa, 2004

[10] A. Kelly, "Mobile Robot Localization from Large Scale Appearance Mosaics", International Journal of Robotics Research 19 (11), 2000

[11] G. Alenyà, J. Escoda, A. B. Martínez, C. Torras, "Using laser and vision to locate a robot in an industrial environment: A practical experience". IEEE International conference of robotics and automation. Barcelona, 2005

[12] J. A. Pérez, J. A. Castellanos, J. M. M. Montiel, J. Neira, J. D. Tardós, "Continuous Mobile Robot Localization: Vision vs. Laser". IEEE International conference of robotics and automation. Detroit, 1999